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# MODELING OF HYDROGEN POTENTIAL AND COMPRESSIVE STRENGTH OF GEOPOLYMER CONCRETE

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## ABSTRACT

*The quality of alkaline liquids used in the activation of geopolymer concrete (GPC) is one of the key parameters that influences the strength of geopolymer concrete. Several studies have been conducted on the mechanical and durability properties of geopolymer concrete but the effect of variation of alkaline liquids' quality on the strength of geopolymer concrete is still limited. Consequently, the study investigates the effect of hydrogen potential (pH) value of the alkaline liquids used in the activation of GPC mix by considering six different available products of sodium hydroxide (NaOH) pellets. Ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) were utilized as source minerals, and the grade 30 (M30) concrete was adopted as mix design proportion. Sodium hydroxide pellets were prepared in 14 molar concentrations. The pH values of alkaline liquids (ALs) and the compressive strengths of the concrete were determined. The experimental findings reveal the best compressive strength with a pH value of 13.75 at 28 days curing for product A compared with pH values of 13.64, 13.61, 13.53, 13.21, and 12.89 for products B, C, D, E, and F respectively. Therefore, it is deduced that higher pH value of ALs results in higher compressive strength of GPC. The developed regression model can thus be used to predict the relationship between pH of ALs and compressive strength of GPC.*

**Key words**: Geopolymer Concrete, Regression Model, Sodium Hydroxide, Sodium Silicate, Compressive Strength.

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# 1. INTRODUCTION

Geopolymer concrete is an emerging and inorganic aluminosilicate polymer synthesized from the source minerals of geological origin or industrial byproducts, dissolved in an alkaline liquids and subsequently polymerized to form a 3D polymeric structure of Si-O-A-O bonds [1]. Reference [2] opined that geopolymeric mechanisms majorly depend on the chemical and mineralogical compositions of source materials, the type and concentration of alkaline liquids, the water content, and the curing temperature. The reaction mechanisms that take place in fresh geopolymer concrete and Portland cement concrete are polycondensation and hydration respectively. Unlike polycondensation, the presence of Portlandite ($CaOH_2$) is attributed to the high pH of cement, and when added to the concrete mix, Portlandite is utilized and the pH of the concrete mix decreases after setting due to the formation of hydration products such as calcium-silicate-hydrate (C-S-H), ettringite, and others. The polycondensation of geopolymeric mix according to [3] involves a serial of chemical reactions between the source materials (aluminosilicate minerals) and the alkaline liquids, and the polycondensation products (calcium-silicate-aluminate-hydrate) paste remain stable between the pH values of 11 and 13. In addition, this solution protects the steel reinforcement from being corroded due to the formation of a thin oxide layer. Moreover, a reduction in the pH level may break the layers as a result of carbon dioxide and sulfide decomposition from the atmosphere, and this worsens the condition because chloride ions will be penetrated from the surrounding. Furthermore, a reduction in pH of concrete is also attributed to the carbonation process. Thus, pH plays a vital role in the chemical kinetics of those reactions and offers a significant information when examining their development in the course of setting and hardening mechanisms [4]. It is a vital parameter in the chemistry of concrete. Reference [5] defined pH as the negative logarithm of the hydrogen ion ($H^+$) concentration that approximately measure the basicity/alkalinity or the acidity of a solution. The scale of pH is ranged from 0 to 14, and a pH value of 7 is conceived to be neutral. Solution with a pH value less than 7 is considered acidic, and the solution with pH value more than 7 is basic. Typically, concrete starts its life at a highly alkaline pH of around 13. Reference [6] established that any solution contains both $H^+$ and $OH^-$ ions and the excesses of both $H^+$ and $OH^-$ ions in the solutions are termed acidic and basic solutions respectively, and when added to water, the equilibrium moves to the left and the $OH^-$ ions decreases; while the equilibrium moves to the left and the $H^+$ ions decreases for both acidic and basic solutions respectively. Geopolymerization mechanism and factors influencing its evolution was also investigated by [7], it was discovered that the strength measured from samples of pH 14 were five times greater than samples formed from pastes of pH 12, and they concluded that a pH range of 13-14 was most suitable for the formation of geopolymers with higher mechanical strengths. Thus, this study considers the curing of specimens in ambient conditions at 28 days in order to replicate its utilization in the field by eliminating heat curing of fresh geopolymer concrete which happens to be uneconomical and impracticable in the construction field. The ratio of sodium silicate-to-sodium hydroxide solutions was selected as 2.5 based on the relevant studies [8] while the GGBFS and CCA were utilized based on the relevant studies [3, 9, 10, 11, 12, 13]. In addition, percentage replacement levels was selected based on the applicable studies [14]. Moreover, this study eliminates weaknesses in the design of GPC mix design proportion by considering the specific gravities, water absorption capacity, and the moisture contents of materials used in the concrete mix designing purpose.

# 2. MATERIALS AND METHODS

## 2.1. Materials

Aggregates sourced from dealers in Ota, Nigeria, and were used in saturated surface dry condition (SSD) with 12.5mm and 19mm size of coarse aggregate. Sodium silicate solution (water glass), sodium hydroxide pellets were sourced from chemical dealers in Lagos, Nigeria. Water from laboratory was used for preparation and mixing purposes. A digital waterproof pH multi metre was employed to determine the temperatures and the pH values of the alkaline liquids and is shown in Fig. 1. Granulated blast furnace slag was obtained from Federated Steel (Nigeria) Limited, Sango-Ota, Nigeria. It was dried, ground, and then sieved with BS 90 μm sieve. Corncobs were gotten in Agbonle, Nigeria, and burnt by open process. It was also sieved with BS 90 μm sieve. The chemical compositions of both GGBFS and CCA were determined by X-Ray Fluorescence (XRF) in Lafarge Holcim Plc, Sagamu, Nigeria. The results of chemical compositions is presented in Table 1.

**Figure 1** A digital pH multi metre

**Table 1** The chemical compositions of GGBFS and CCA

| Composition | CaO | SiO2 | Al2O3 | Fe2O3 | SO3 | MgO | Na2O | M.C | LOI |
|---|---|---|---|---|---|---|---|---|---|
| **GGBFS (%)** | 36.52 | 35.77 | 14.11 | 0.92 | 1.08 | 9.45 | 0.30 | 0.52 | 0.32 |
| **CCA (%)** | 12.62 | 60.50 | 8.78 | 9.13 | 1.25 | 1.23 | 0.65 | 1.25 | 0.49 |

Notes: M.C (Moisture Content); LOI (Loss of Ignition)

## 2.2. Methods

### *2.2.1. Determination of Temperatures and pH of Alkaline Liquids.*

The 14 molar concentration of each sodium hydroxide solution was prepared 24 hours prior to use by dissolving 400 grams of each NaOH pellets to 600 grams of clean water. The pH multi metre was first calibrated with the aid of manufacturer's manuals and appropriate buffer solutions. The temperature and the pH value of the liquid constituents were measured using the pH multi metre and the results are presented in Table 2. Thereafter, sodium silicate solution was added to the prepared sodium hydroxide solutions 30 minutes prior to casting and thoroughly mixed for 5 minutes. The results of the combined mixture are presented in Table 3. The average temperature and relative humidity during the preparation and reading were 25$^o$C and 60% respectively.

**Table 2** The pH and temperature of each liquid component

| Liquid Component | pH Value | Temperature (°C) |
|---|---|---|
| Product A + Water | 12.95 | 36.10 |
| Product B + Water | 12.78 | 35.80 |
| Product C + Water | 12.65 | 35.22 |
| Product D + Water | 12.54 | 35.05 |
| Product E + Water | 12.29 | 34.46 |
| Product F + Water | 12.10 | 34.15 |
| $Na_2SiO_3$ | 12.25 | 25.00 |
| Water | 9.00 | 23.00 |

**Note:** Product A denotes JSC Kaustic of NaOH pellets;

Product B denotes J. T Baker of NaOH pellets;

Product C denotes Sigman Aldrich of NaOH pellets;

Product D denotes Fischerman of NaOH pellets;

Product E denotes Henan Fengbai of NaOH pellets;

Product F denotes Xingtai Hebang of NaOH pellets

**Table 3** The pH and temperature of the combined mixture

| Combined Mixture | pH Value | Temperature (°C) |
|---|---|---|
| Product A + $Na_2SiO_3$ + Water | 13.75 | 32.42 |
| Product B + $Na_2SiO_3$ + Water | 13.64 | 31.75 |
| Product C + $Na_2SiO_3$ + Water | 13.61 | 31.25 |
| Product D + $Na_2SiO_3$ + Water | 13.53 | 30.68 |
| Product E + $Na_2SiO_3$ + Water | 13.21 | 30.05 |
| Product F + $Na_2SiO_3$ + Water | 12.89 | 29.95 |

### *2.2.2. Determination of Physical Properties of Materials used*

The physical properties of materials used were carried out at civil engineering laboratories, Covenant University, Ota, Nigeria. The specific gravities of sodium hydroxide pellets and sodium silicate gel were obtained from the manufacturers' manuals, and the results are presented in Table 4.

**Table 4** The physical properties of materials used

| Material | Specific Gravity (%) | Water Absorption (%) | Fineness Test BS 90 µm residue (%) | Moisture Content (%) |
|---|---|---|---|---|
| Cement | 3.15 | - | 7.7 | - |
| CCA | 2.44 | - | 7.4 | - |
| GBFS | 2.90 | - | 7.3 | - |
| FA | 2.60 | 0.7 | | 0.3 |
| Combined CA | 2.64 | 0.8 | | 0.2 |
| NaOH | 1.49 | - | | - |
| $Na_2SiO_3$ | 1.60 | - | | - |

Notes: FA (Fine Aggregates); CA (Coarse Aggregates- 12.5 mm and 19 mm sizes)

### *2.2.3. Concrete Mix Design*

The concrete mix proportion was designed in consonant with [15, 16] to arrive at initial mix proportions and considered the specific gravities, water absorptions, and moisture contents of constituents in order to attain true mix. The mix replacement levels of GGBFS: CCA are 100: 0%, 80: 20%, 60: 40%, 40: 60%, 80: 20%, and 0: 100% denoted by Mix 1, Mix 2, Mix 3, Mix

4, Mix 5, and Mix 6 respectively. The quantity of mixture proportion for the concrete constituents is summarily presented in Table 5.

**Table 5** Quantity of concrete ingredients (kg/m$^3$)

| Mix ID | GGBFS | CCA | CA 1 | CA 2 | FA | SS | SH | AL/B | W/S |
|---|---|---|---|---|---|---|---|---|---|
| Mix 1 | 390 | 0 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |
| Mix 2 | 312 | 78 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |
| Mix 3 | 234 | 156 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |
| Mix 4 | 156 | 234 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |
| Mix 5 | 78 | 312 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |
| Mix 6 | 0 | 390 | 516 | 516 | 675 | 150 | 60 | 0.54 | 0.26 |

Note: CA 1 (12.5mm Coarse Aggregate size); CA 2 (19mm Coarse Aggregate size); FA (Fine Aggregate); SS (Sodium Silicate solution); SH (Sodium Hydroxide solution); SP (Superplasticizer); AL/B (Alkali Liquid/Binder- for GPC, and Water/Binder- for PCC); W/S (Water-to-Geopolymer Solids ratio).

### *2.2.4. Mixing and Casting of Fresh Concretes*

Both dry and liquid constituents was thoroughly mixed for 5-6 minutes until homogeneity was obtained. The fresh mix was manually cast, and then filled in the moulds and compacted accordingly. The fresh GPC specimens were kept in rest period for 72 hours before being removed from the cubes to allow for proper polymerization. All samples were cured at room temperature in ambient condition (23 ± 5 $^oC$; 60% ± 5% RH). For each mixture, three samples were prepared for each testing age.

### *2.2.5. Tests Methods*

Compressive strength for each mix was determined according to [17]. A digital testing machine with 2000 KN maximum capacity was used for the specimens testing as shown in Fig. 2.

**Figure 2** Experimental testing machine

## 3. RESULTS AND DISCUSSIONS

### 3.1. Chemical Compositions

The results of the chemical compositions for GGBFS in Table 1 indicate that it is suitable for use as a slag since it satisfies the requirements of [18] which specifies silicon dioxide ($SiO_2$) + calcium oxide (CaO) + magnesium oxide (MgO) ≥ 67%, and LOI < 3.0%. Similarly, the chemical compositions of CCA used meet the specifications of [19] which recommends silicon dioxide ($SiO_2$) + aluminium oxide ($Al_2O_3$) + iron oxide ($Fe_2O_3$) ≥ 70%, and LOI < 10.0%. Hence, desirable for use as a pozzolanic material.

### 3.2. pH and Temperature

The product A from Table 2 has a higher pH value of 12.95 and a higher temperature of 36.10°C when compared with other products. The increase in pH may be attributed to the more increase in $OH^-$ ions and more decrease in $H^+$ ions when the product A pellets is added to the water while the increase in temperature indicates that more exothermic reaction is evolved when product A pellets is dissolved in water though, cool down to ambient condition. These findings are in line with [6] that increase in pH signifies decrease in $H^+$ ions while the $OH^-$ ions increase as the water equilibrium moves to the left. The sodium silicate solution has a pH value of 12.25. This is in agreement with [20] that commercial silicate solutions have a pH value in the range of 10-13. Moreover, the pH value of water shows 9.00. This is also in consonant with [21] which states that the pH value of water for use in concrete should be greater than or equal to 4. The combined mixture in Table 3 compared with the values in Table 2 connotes that product A has an increase in pH value and a decrease in temperature by 5.82% and 10.19% when added to the sodium silicate respectively. Similar trends occur to other products. The increase in pH value may be deduced by the addition of sodium silicate to the sodium hydroxide solution. This is conformed to the finding by [6] that if alkaline solution is added to a solution of a pH value ≥ 9, the pH would increase.

### 3.3. Main Effect and Correlation between pH and Temperature

The influence of temperature on the pH was assessed by main effect plot using Minitab 17. The result is presented in Fig. 3, and it signifies that temperature has effect on the pH of alkaline liquid when it is added to the water since the plotted line is not parallel to the horizontal line of overall mean (13.44).

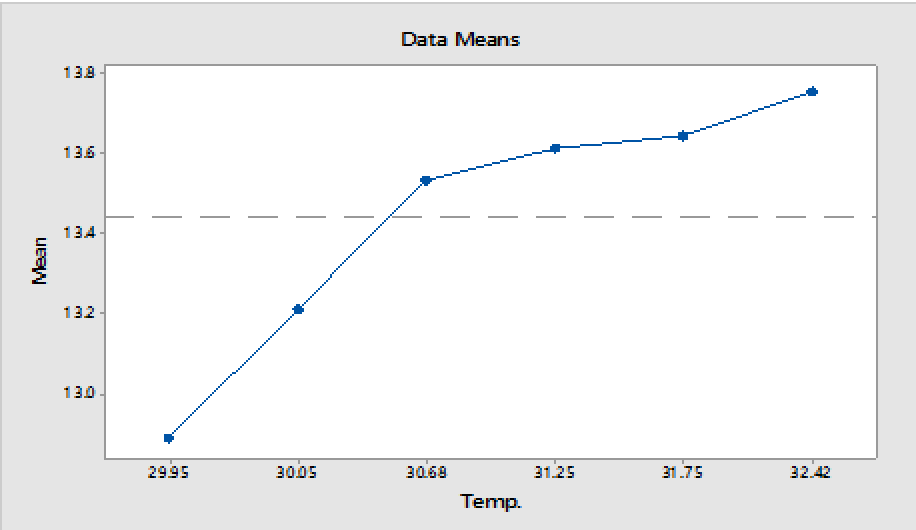



**Figure 3** Main effect plot for pH

Moreover, the strength and direction of the relationship between the pH and the temperature of the alkaline liquids are evaluated using the Pearson correlation in Minitab 17. The result is presented in Fig. 4, and it indicates that both temperature and pH are highly correlated and perfectly aligned because the Pearson correlation of both pH and temperature is 0.884 and this is greater than 0.7000.

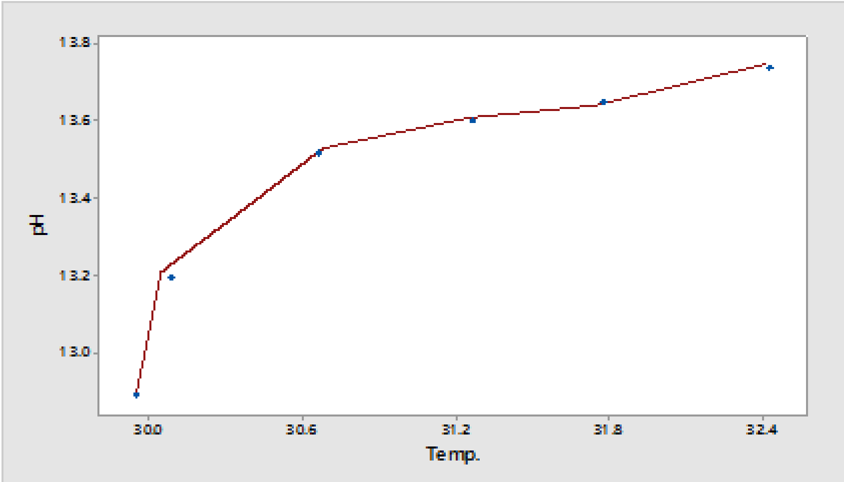
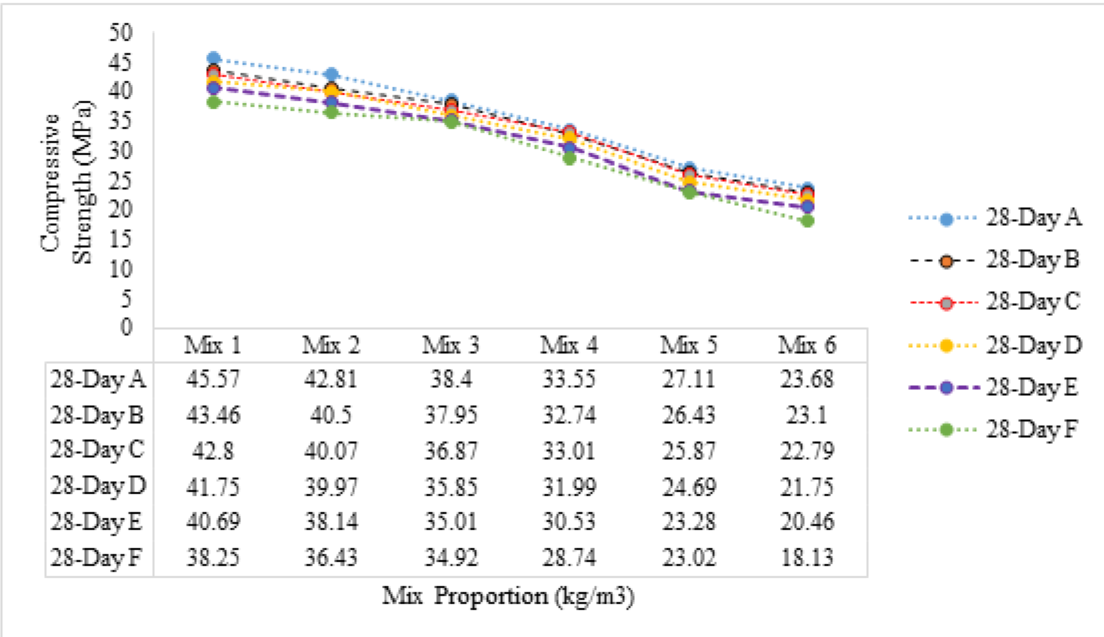



**Figure 4** Pearson correlation of pH and temperature

## 3.4. Compressive Strength

The results of the compressive strengths as shown in Fig. 5 show that compressive strength increases as GGBFS replacement level increases. The results reveal that 14 Molar concentration of NaOH exhibits the highest compressive strength with 45.57 MPa at 28 days curing for product A compared with 43.46 MPa,42.80 MPa, 41.75 MPa, 40.69 MPa, and 38.25 MPa for products B, C, D, E, and F respectively at the same curing conditions. The higher strength of product A compared with other products infers that higher pH is required for geopolymeric formation with higher strength, and this is agreeable to [7] that Ph values of range 13-14 are suitable for the polymeric development with higher mechanical strengths.




| | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 | Mix 6 |
|---|---|---|---|---|---|---|
| 28-Day A | 45.57 | 42.81 | 38.4 | 33.55 | 27.11 | 23.68 |
| 28-Day B | 43.46 | 40.5 | 37.95 | 32.74 | 26.43 | 23.1 |
| 28-Day C | 42.8 | 40.07 | 36.87 | 33.01 | 25.87 | 22.79 |
| 28-Day D | 41.75 | 39.97 | 35.85 | 31.99 | 24.69 | 21.75 |
| 28-Day E | 40.69 | 38.14 | 35.01 | 30.53 | 23.28 | 20.46 |
| 28-Day F | 38.25 | 36.43 | 34.92 | 28.74 | 23.02 | 18.13 |

**Figure 5** The graph of compressive strength against mix proportion

## 3.5. Regression Model

Matlab R 2017a was employed and the best values of compressive strengths for all products were selected for the regression analysis and the model equation is presented in Fig. 6. The coefficients of determination ($R^2$) signifies that the model is 91% significantly fit to predict the relationship between the compressive strength and the pH, and also, compressive strength largely depends on the pH at 95% confidence bounds.

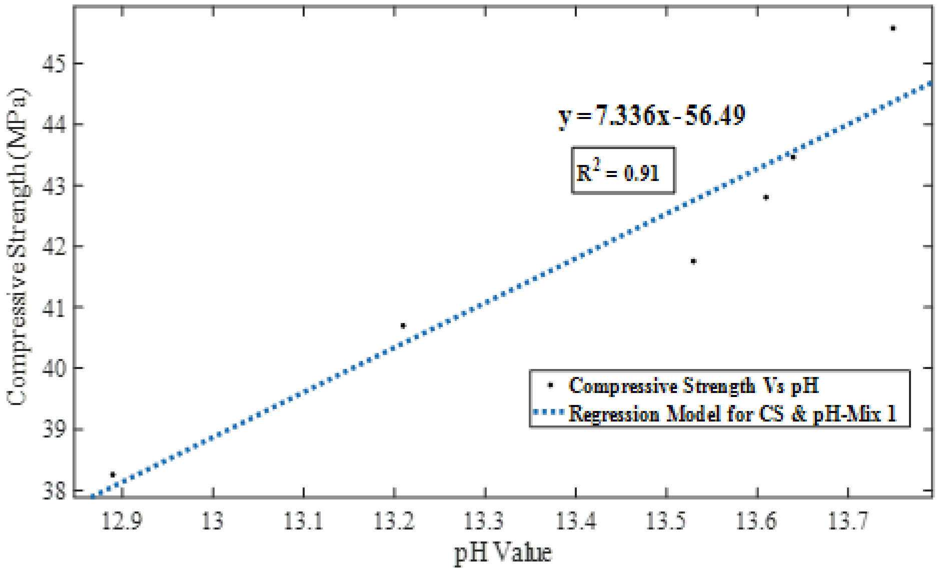



**Figure 6** Regression model for the concrete

## 4. CONCLUSIONS

Based on the experimental results, it is concluded that higher value of hydrogen potential (pH) exhibits higher compressive strength in geopolymer concrete. For the best performance in the mechanical property of GPC, the study thus recommends that pH values of the alkaline liquids should be examined before being used as activators in the production of GPC and also, adopt the developed model equation of this study to predict the compressive strength in respect to the pH value.

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